A GENERALIZED APPROACH FOR EVALUATING LOGISTICS STRATEGIES DURING ADVANCE PROCUREMENT PLANNING

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THESIS

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by

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A Generalized Approach For Evaluating Logistics Strategies During Advance Procurement Planning

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements for the degree of

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March 1975

ABSTRACT

This thesis presents a methodology for evaluating competitive logistics strategies early in the acquisition sequence. The author reviews the system requirements determination process and defines the role of advance procurement planning. Within this context, a system model is developed which provides visibility of the cost and effectiveness impacts of alternative combinations of reliability, maintainability, and supportability parameters.

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I. INTRODUCTION

Increasingly, the programs of the Department of Defense are being challenged by members of Congress, the media, and concerned segments of the body politic. Prominent among the antecedents of this condition are emergent non-defense priorities and the concomitant rivalry for scarce public resources, and the spiraling costs of procuring, operating, and supporting the military structure. To ensure that its resources are efficiently utilized to attain an acceptable level of total force effectiveness, the Department has promulgated policies responsive to this dynamic environment. Central to these are efforts designed to improve the weapons system acquisition process in general, and its logistic support aspects in particular. This is a direct reaction to the magnitude of a system's life cycle cost experienced during its deployment phase.

In the Fiscal Year 1975 Annual Defense Department Report [Ref. 1], Secretary of Defense Schlesinger noted:

> The improvement of reliability, maintainability and life cycle support of new weapons is receiving increased emphasis within DoD. Logistic support is a major design parameter with the objective of reducing the number of equipment failures, cutting repair costs, and decreasing distribution and inventory costs of components through greater standardization. To assure that design objectives are reached and that required support planning has been accomplished, a plan for logistic support has been made an integral part of weapon system development plans. Demonstration that logistic design parameters have been achieved is a major objective of developmental and operational testing and evaluation. System program managers have been charged with the responsibility for assuring that support resource requirements are integrated

with operational requirements to accomplish successful deployment of new systems.

In this context, the role of logistics engineering becomes more prominent. The need to coordinate reliability, maintainability, and support considerations into acquisition planning and system design must be affirmed if the adverse effects of possible budgetary strictures are to be neutralized and the defense mission effectively discharged. This requires that procurement personnel be aware of these factors and their implications for costs and benefits throughout the life cycle. Furthermore, the possibility of enhancing the operational value of systems by creatively applying logistics strategies appears to warrant continued study.

II. STATEMENT OF PURPOSE

The objective of this research was to provide an operational construct for considering, in the early phase of advance procurement planning, the life cycle impact of both costs and effectiveness of a weapon system as influenced by reliability, maintainability, and supportability. To this end, the principal thrust was on three facets of system acquisition: requirements determination, the advance procurement planning function, and the role of economic analysis. This involved:

-reviewing the system requirements determination process in order to distinguish its characteristics in the several phases of the life cycle,

-identifying the demands placed upon the advance procurement planning function, and the level of analytic sophistication and informational needs required to equal those demands, and

-formulating an economic analysis methodology for addressing the system impacts of logistics alternatives over time.

Figure (1) depicts the relationships among these several areas. It was intended that this thesis be directed at procurement personnel not already familiar with the logistics engineering disciplines.

III. METHOD OF RESEARCH

Initially, an extensive literature search was conducted. The files of the Naval Postgraduate School and the Defense Documentation Center (Cameron Station, Va.) were queried with respect to their holdings in the requirements determination and logistics areas. Relevant materials were obtained from both sources.

In July, 1974, an opportunity to interview participants in the F-14/PHOENIX weapons system acquisition arose. Availing of this timely circumstance, a one week trip to Washington, D.C., and Bethpage, New York, was completed. Discussions pertaining to requirements determination, reliability, maintainability, and supportability were conducted with government and contractor personnel. Included were representatives from the F-14/PHOENIX Project Office (PMA-241), NAVAIR functional codes, Navy Fighter Study Group, and Grumman Aerospace Corporation (GAC). Throughout

SELECTED ELEMENTS OF THE ACQUISITION ENVIRONMENT

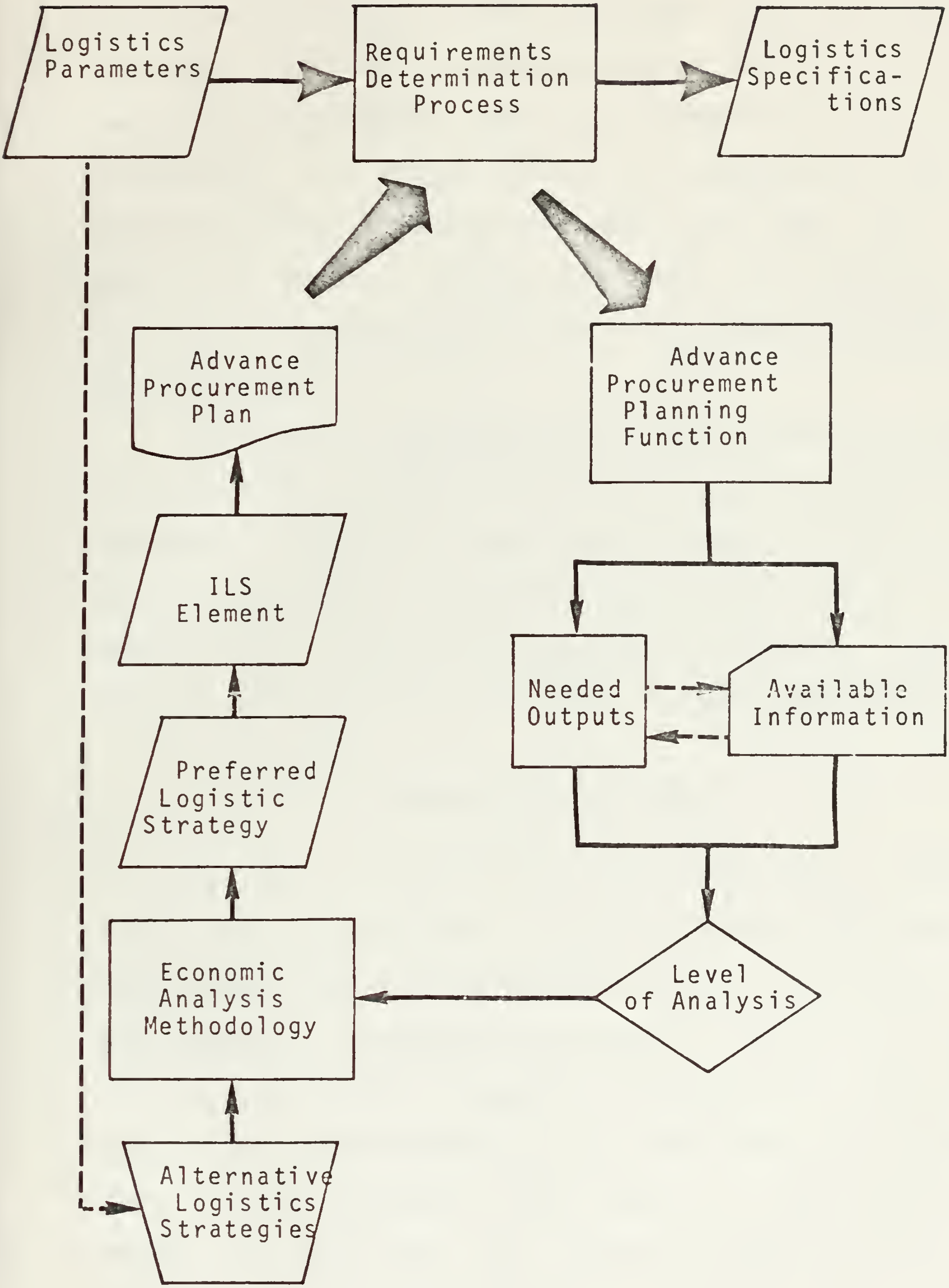

Figure (1)

the following several months, telephone exchanges with these and other individuals from the Aviation Supply Office and the U.S. Naval Weapons Engineering Support Activity were transacted. As a direct result, F-14 documents in the discussion areas were made available for study. This experience tempered concepts and theory with the very practical, day-to-day aspects of requirements determination and logistics.

Additionally, participation in two courses not normally included in the Systems Acquisition Management curriculum provided a conceptual scheme and an appreciation for the analytic techniques required in any research effort. The courses were "Investigative Methods of Economics" and "Methods and Practices of Systems Analysis (Costing)."

IV. ORGANIZATION OF THESIS

The thesis is divided into two major parts. Section V establishes definitions of relevant terms, discusses the system requirements determination process, and presents the environment of the advance procurement planning function. Section VI describes a general methodology for analyzing reliability, maintainability, and supportability alternatives early in the acquisition sequence. This format was chosen such that lower level elements of the structure would be viewed in the perspective of their larger functions. Conclusions and suggested areas for further study are noted in Section VII.

V. THE PROCESSES

A. PRELIMINARY DEFINITIONS

In determining the effectiveness (E) of a given system, one is attempting to ascertain the degree of mission fulfillment which can be expected within the qualifications of expressed assumptions. As such, it has been mathematically defined in a comprehensive model as the product of three measures: availability, dependability, and capability [Ref. 2]. As sub-indices, these terms are characterized by additional concepts and parameters, but more importantly, identifiable engineering specialties provide their foundations. These include reliability (R), maintainability (M), and logistic support (S). Figure (2) illustrates the relationships involved in this scheme. It should be noted that R, M, and S are the principal determinants of availability and dependability, and therefore to the overall measure, system E. When analyzed in conjunction with cost, E provides the positive input toward establishing the operational value of the system.

In contrast to the benefits represented by E, cost may be interpreted as the input measure sacrificed in order to realize those benefits. Fisher [Ref. 3] has distinguished among several categories of cost, ranging from dollar expenditures to non-quantifiable costs (e.g., social costs). For these purposes, it is sufficient to note that the most important criterion in determining the relevant measure of

EFFECTIVENESS MODEL

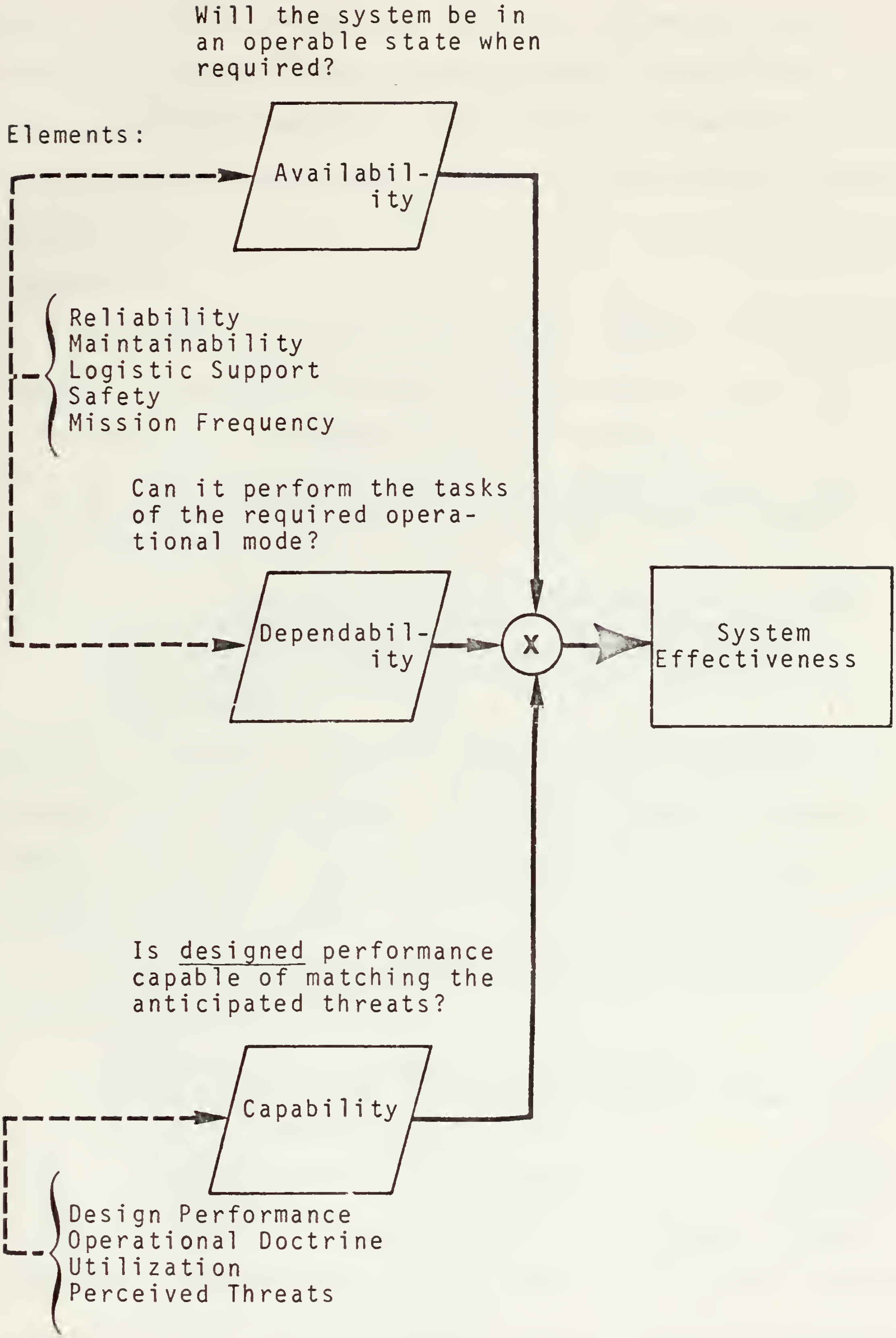

Figure (2)

cost is that it adequately represent the magnitude of benefits foregone when selecting among alternatives. Examples of these opportunity costs include out-of-pocket cash expenditures, direct labor hours, or the amount of repair parts inventory required to achieve an assigned mission objective.

R and M are two closely aligned disciplines which are often implemented in concert. MIL-STD-721B [Ref. 4] provides stochastic definitions as follows:

> R: The probability that an item will perform its function for a specified interval under stated conditions.
>
> M: The probability that an item will be retained in or restored to a specfied condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources.

Figure (3) notes activities common to both and their sequential relationships. The dynamic R and M program ensures that its elements are responsive to the most recent demands on the system.

While not explicitly defined in Ref. 4, a first approximation to S might be:

> S: The probability that a serviceable item is available to repair or replace a failed item within a given period of time.

This is the substance of the integrated logistic support (ILS) problem. S includes planned maintenance, support personnel and equipment, spares and repair parts, facilities, technical data and publications, and contract maintenance. As such, a functional dependence exists among the various R, M, and S elements.

THE R AND M PROGRAM

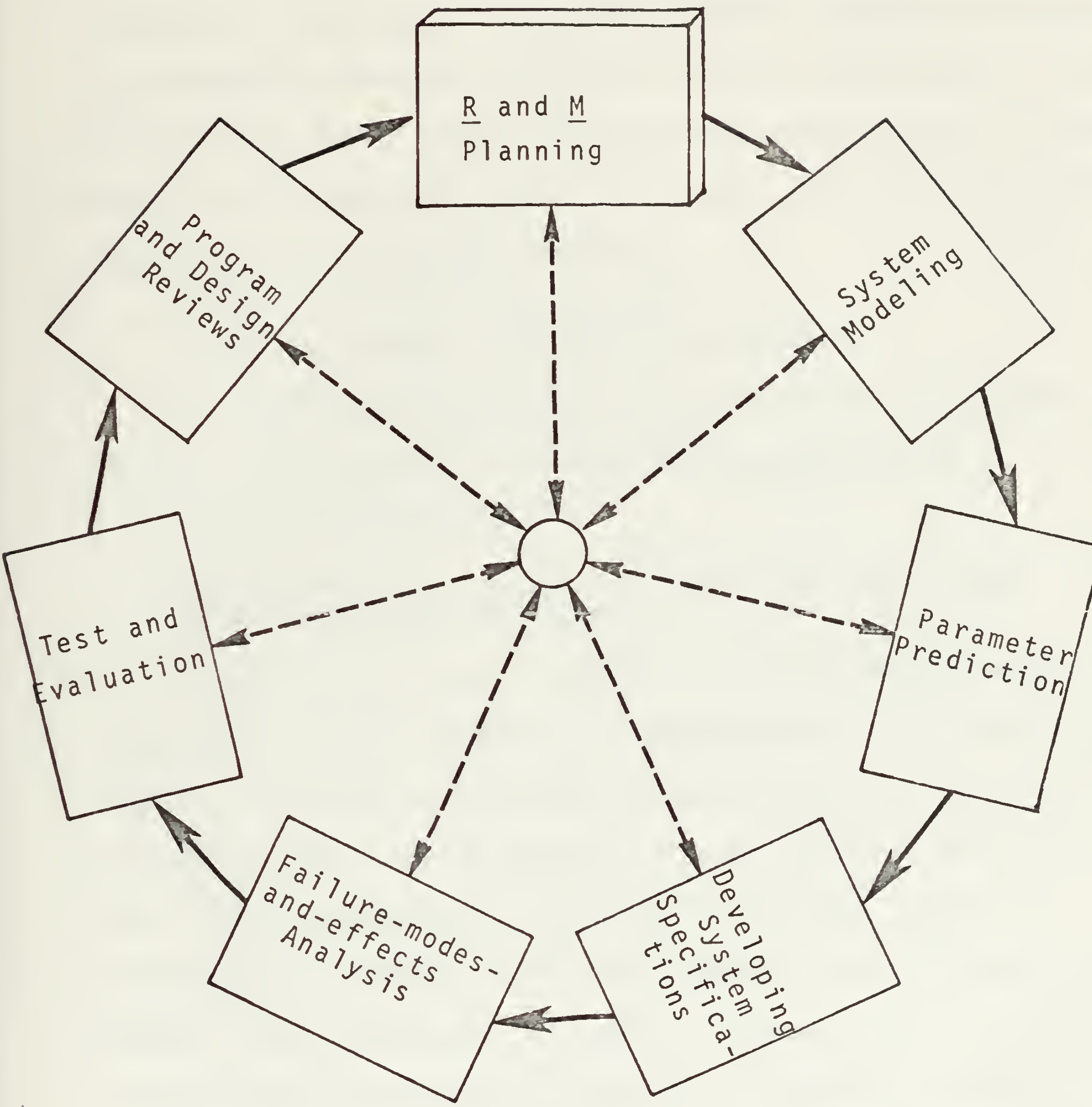

Figure (3)

The scope of the support effort resulting from a given logistic strategy (i.e., a unique combination of R, M and S parameters) is costly in terms of manpower, time, and material. Therefore, strategy elements should be subjected to a rigorous tradeoff procedure in the same manner as other design variables. Such a methodology would assure a viable and effective system, taken as a whole, which is consonant with relevant resource limitations.

B. THE REQUIREMENTS DETERMINATION PROCESS

In theory, system design and development activities are guided by the results of either of two methods of constrained optimization:

-minimizing cost subject to ensuring some fixed level of "required" E, or

-maximizing system E within a predetermined budget.

Because the focal problem is fundamentally the same, the results obtained by employing either method in an analysis are equivalent. Microeconomic theory utilizes the first to resolve the producer's problem of selecting factors to minimize his expenditures while maintaining a given rate of output. The consumer's problem of maximizing utility by arranging his purchases of goods and services within a fixed money income is representative of the second technique. If one substitutes "Department of Defense's" for "consumer's" and "E" for "utility", the basics of the current "design to cost" philosophy emerge.

In this context, the performance requirements or design specifications of a new system are the product of several types of analyses in the iterative process noted in figure (4). Initially, a thorough threat identification and evaluation study is conducted to define operational deficiencies and establish a gross approximation to the mission. Feasible technical approaches are then superimposed on these operational considerations (the Service document outlining these considerations is the Operational Requirement, described in Ref. 5). The concepts are refined to the point where sufficient detail exists to propose performance envelopes and, in turn, to synthesize alternative configurations. Candidate systems are optimized on paper and evaluated in terms of mission fulfillment (E), cost, and schedule thresholds. A preferred design(s) is (are) subsequently selected for further development. The important output of the process at this point is a set of system design specifications to be used during the production phase. If all alternatives are rejected, the procedure is replicated until a feasible, suitable, and acceptable system evolves.

The feedback feature of the process makes available current data to each activity, and facilitates a design which is capable of fulfilling the prevailing mission requirements. An example of this would be the utilization of operational data from the first production lot already in service as a basis for modifying succedent lots. Also,

SYSTEM REQUIREMENTS DETERMINATION PROCESS

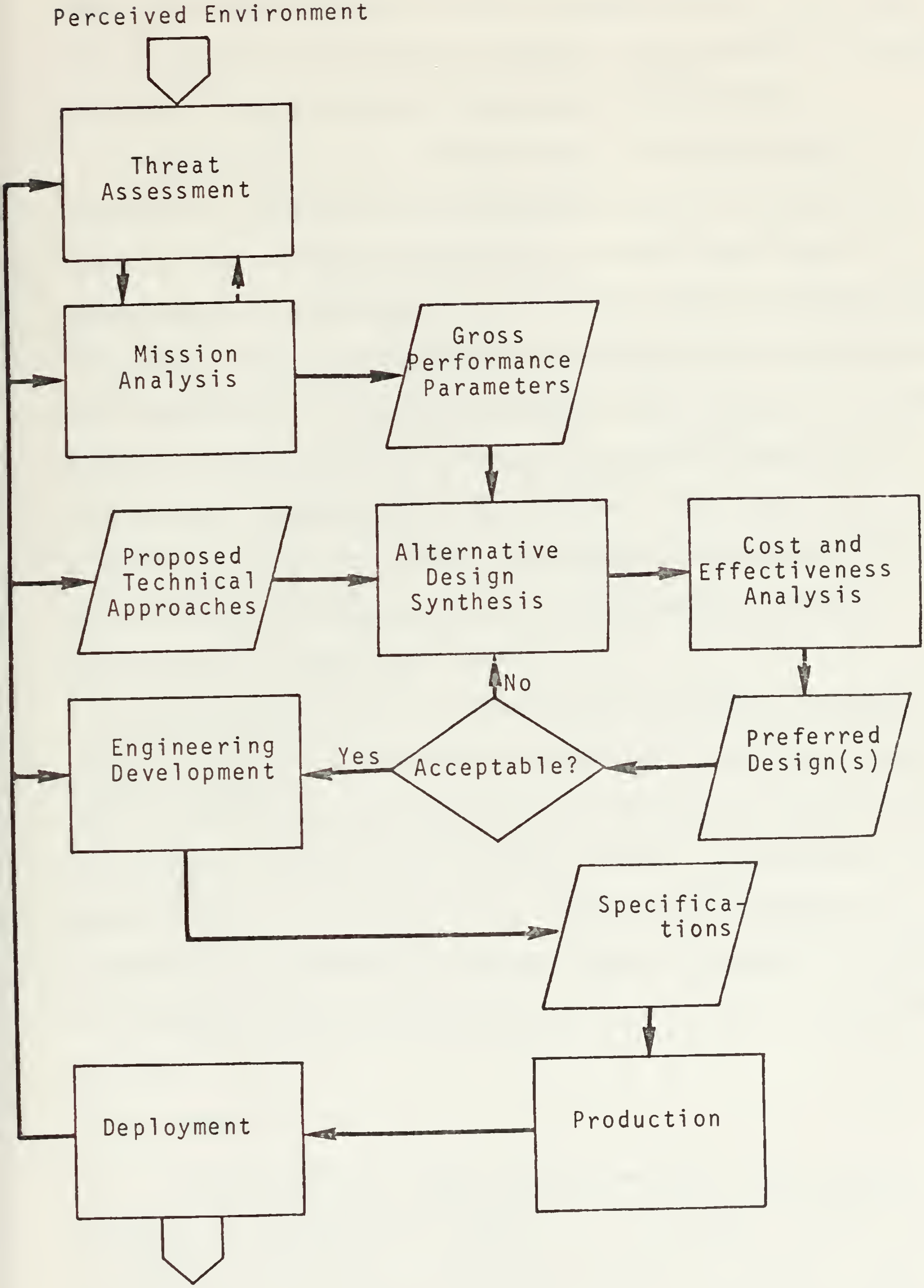

Figure (4)

the evolutionary nature of most systems demands that this data be used to generate performance requirements or design specifications of future replacement generations.

Although this is a simple model, it does serve as a convenient framework for introducing several forces which distort the process in practice. In the first place, uncertainty is manifest throughout the initial phases of the life cycle and persists in varying degrees into production and deployment. Threat, performance, and technical unknowns surface in the form of alternate design configurations, engineering changes, and modifications. As such, a significant objective of the conceptual, validation, and full-scale development phases is to continually reduce uncertainty at each iteration.[1]

Secondly, the forces generated by changing program budgets, unrealistic Initial Operational Capability dates, and the differing responsibilities and perspectives of the principals involved (e.g., OPNAV, NAVAIR, and GAC) act in a manner harsh to accurate predictions of the system constraints. The combined effects reduce the extent of either of the two optimization methodologies to system sub-optimization.

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[1]Fisher [Ref. 6] notes several methods for managing these "requirements", or state-of-the-world uncertainties. Included are sensitivity analysis, contingency analysis, a fortiori analysis, supplemental discounting, and the use of adjustment factors. A credible body of opinion holds their use in a rigorous process prior to source selection should reduce the effects of these kinds of uncertainties in the future [Ref. 7].

Thirdly, experience indicates that the operating and support costs of a weapon system over its life cycle may be several times the procurement cost. R, M, and S parameters have a substantial effect on these cost elements. As such, they should not be established independently of other design variables, but rather afforded equal status, with cost and schedule, in the requirements determination process. Typically, however, system requirements are divided into two groups of unequal importance. While speed, thrust, weight, etc. are accorded primary emphasis, the logistics disciplines are relegated a secondary role [Ref. 8]. This situation arises primarily as a result of both institutional bias and the terms of the contractual instrument employed in the exchange. The contractor is usually motivated to pursue the performance requirements because this is what the customer has communicated to him, both formally and informally. In addition, less than adequate acceptance testing and the lack of contractor financial responsibility for system operation and support provide an impetus for the contractor to slight R, M, and S if benefits will accrue in other areas of the program.

In conclusion, the proper focus of the requirements determination process is to design and develop a system which will both counter the threat and be affordable in terms of procurement, operating, and support costs. With a deeper understanding of the significant impact of the logistics disciplines, procurement personnel can establish

realistic requirements and consider different methods of reducing life cycle costs. Johnson and Reel [Ref. 9] have indicated that the analysis of alternative logistics strategies is most productive if conducted during the early phases of the life cycle. In this manner, the disproportionately high costs of support actions in the use environment may be reduced and the realized savings more efficiently utilized in serving the operating forces.

C. ADVANCE PROCUREMENT PLANNING

Advance procurement planning refers to those activities initiated early in the system life cycle, prior to any contractual arrangement, to formulate a business plan for the tentative development and procurement of a system. These activities are crystallized in a document known as the Advance Procurement Plan (APP). The primary thrust of the APP is to coordinate the efforts of all responsible personnel for the purpose of obtaining the required items in the proper amounts and of sufficient quality, on time, and at a fair and reasonable price. Both the <u>Armed Services Procurement Regulations</u> (ASPR Part 21) and the <u>Naval Procurement Directives</u> (NPD 1-2100) denote the relevant statutory and policy requirements of this function.

Advance procurement planning should be initiated as soon as the Operational Requirement is assigned to the principal development activity by the Chief of Naval Material. Typically, this would occur during concept formulation/validation. Elements of the APP are noted in

figure (5) [Ref. 10]. This ILS planning element is of particular concern because it is the area in which the objective of this thesis should normally be considered.

ILS planning is oriented toward formulating the support consequences of each design alternative under consideration. Reference 11 provides policy guidance in the areas of required outputs and information requirements for each phase of the system life cycle. Noting that the level of analysis should be consistent with the information needed at a particular phase or for transition to the subsequent phase, it defines the necessary outputs as follows:

> Conceptual: Only a broad general plan for integrated logistic support is needed at this phase, but any special problems should be noted.
>
> Validation: Only special problems of logistics support need be addressed at this phase.

Information which should be considered includes elements of mission and operational data (e.g., E, R, M, mission profiles, and utilization rates) and logistic support data. By systematically analyzing this information, ILS planning provides the means to influence the tradeoffs among design variables within the requirements determination process.

To be sure, the APP represents a potent management tool if utilized fully. As a dynamic document, it reflects the current status of the acquisition while providing the structure for a corporate memory of problem areas, alternatives, and implemented solutions. By effectively employing a robust advance procurement planning process throughout all elements of his organization at the

ELEMENTS OF THE ADVANCE PROCUREMENT PLAN

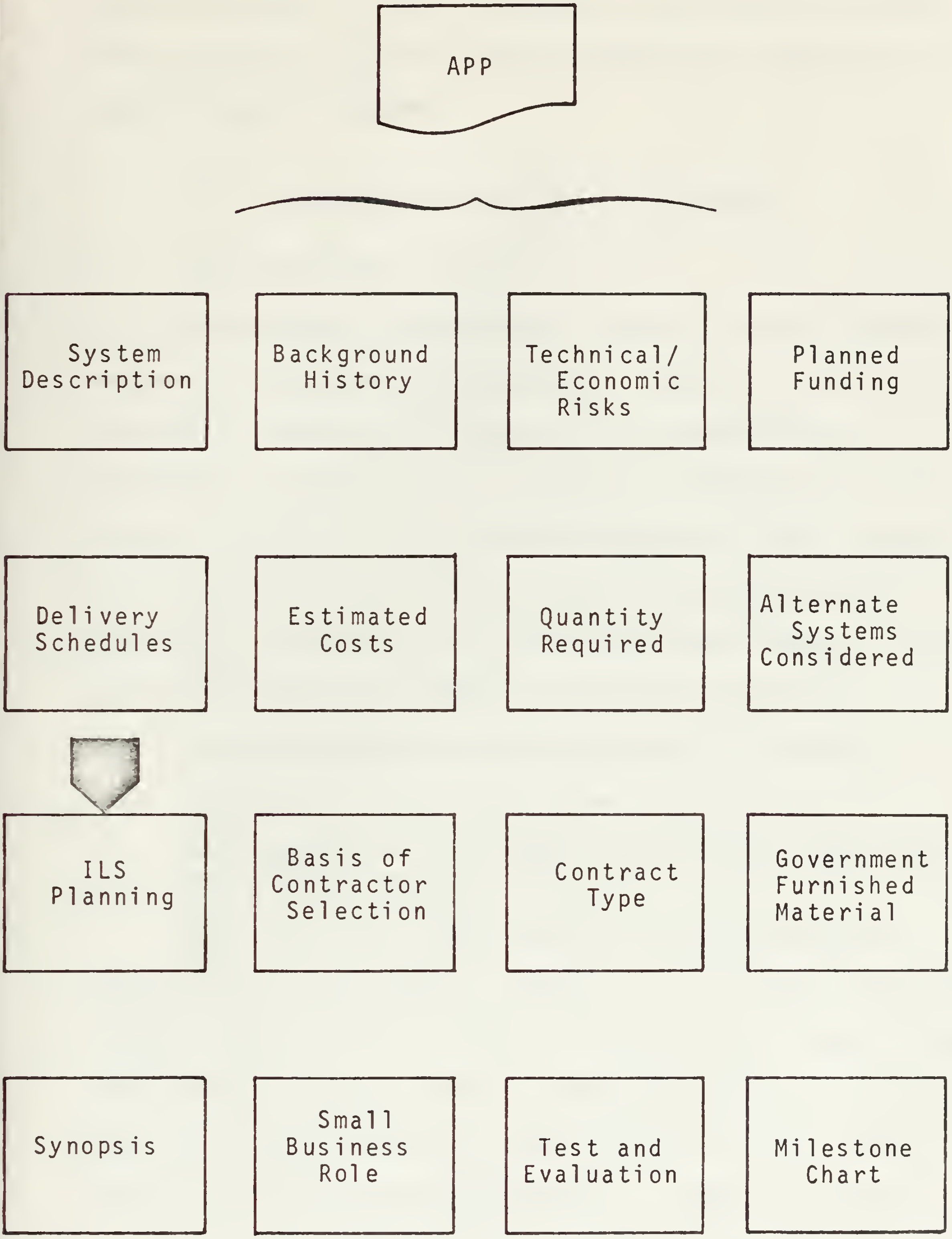

Figure (5)

earliest phases of the life cycle, the Project Manager facilitates a logistic support capability responsive to the acquisition environment.

VI. EVALUATING LOGISTICS STRATEGIES

A. THE PROCUREMENT PROBLEM

The process of acquiring a system is quite complex. Because it embraces many pervasive aspects of planning, analysis, scheduling, budgeting, and contracting, it is difficult to formulate an operative statement which is truely inclusive of the Project Manager's total concerns. For the purposes of this analysis, the problem shall be limited by considering only the following elements during the early phases of advance procurement planning:

-an appropriate measure and level of system $\underline{E}$,

-alternative $\underline{R}$, $\underline{M}$, and $\underline{S}$ specifications,

-the quantities of primary items, spare items, and repair parts required, and

-the life cycle prime costs of system ownership.

Research and development, training, facilities, and similar support requirements are not included because they are more important at higher levels of aggregation than are being proposed, while being less than amenable to the purely variable costing model introduced in later paragraphs.

In the context of this structure, "system" is the total of primary items, spare items, repair parts, and maintenance resources (i.e., user maintenance manhours or contractor support). Primary items are the installed or operating

equipment. Spare items are identical equipment carried in the active inventory with repair parts; both of these elements are utilized in the maintenance process. Prime costs refer to the variable components of direct materials (primary and spare items, and repair parts) and direct labor (user labor rate or unit warranty cost). Focusing on these categories of cost eliminates the arbitrariness of various overhead (indirect costs) allocation schemes.

The essence of the procurement problem encountered by a Project Manager is to define R, M, and S contract specifications for a system while simultaneously considering cost and E. Selection among competitive alternatives is made in an environment of incomplete information, uncertainty, and interactions among the various elements of the decision. To scale down these complexities to manageable proportions, it is assumed that schedule and performance requirements (i.e., delivery dates can be met as specified, and item output equals predetermined minimum acceptable levels) are independent of the logistics specifications listed in the prospective contract. It should be noted that there is an inherent danger in this type of "requirements" approach in that unrealistic schedule or performance demands would seriously violate the simplification.

The Project Manager must realize that the design characteristics he specifies in the contract will limit the operating and support alternatives available to the final user. Compensating for equipment which is not compatible

with its use environment could require increased maintenance and inventory support. Such a course of action undoubtedly increases life cycle costs.

B. THE ALTERNATIVES

This analysis shall focus on two alternative logistics strategies:

-item maintenance and inventory support is to be performed by the final user, and

-item maintenance and inventory support is to be performed by the supplier under a failure-free warranty provision.

Each strategy shall be examined within a three dimensional framework consisting of the stated rules of system operation, the definition of failures relevant to the system, and the equipment failure process.

1. Logistic Strategy I (User Support)

This alternative is composed of the following elements:

a. Primary items are subjected to varying mission requirements at unknown points in time.

b. Primary items are placed in operation immediately upon demand.

c. Item failure is defined as any condition which is at variance with prescribed tolerance limits.

d. If an item is failed at the start of a mission, it is removed by maintenance personnel and replaced with a spare withdrawn from the active inventory. The spare item is then placed in operation.

e. If item failure occurs <u>during</u> operation, it is removed and replaced as before, and the spare item assumes the interrupted mission.

f. Failed items are sent to the maintenance facility where direct materials (repair parts withdrawn from the active inventory) and direct labor (user maintenance manhours) are consumed in the maintenace process.

g. Repaired items are returned to the active inventory, while catastrophic failures are discarded.

Figure (6) pictorially represents this sequence of elements.

2. <u>Logistic Strategy II (Supplier Support)</u>

Within the provisions of a failure-free warranty, the supplier agrees to replace all failed items not consequences of extraordinary abuse from his inventory of new or repaired items. Elements a. through e. of Strategy I are valid within this context. Exceptions to the last two are:

f# Failed items, and the relevant failure data, are forwarded to the supplier for disposition.

g# The supplier has the option of replacing the failed item with either a new or repair item from his inventory. Additionally, he is permitted to make design changes to items for the purposes of <u>R</u> and <u>M</u> improvements at his discretion. The only limits to this grant are that item performance and configuration constraints previously agreed to are not violated.

Figure (7) notes this alternative sequence.

LOGISTIC STRATEGY I

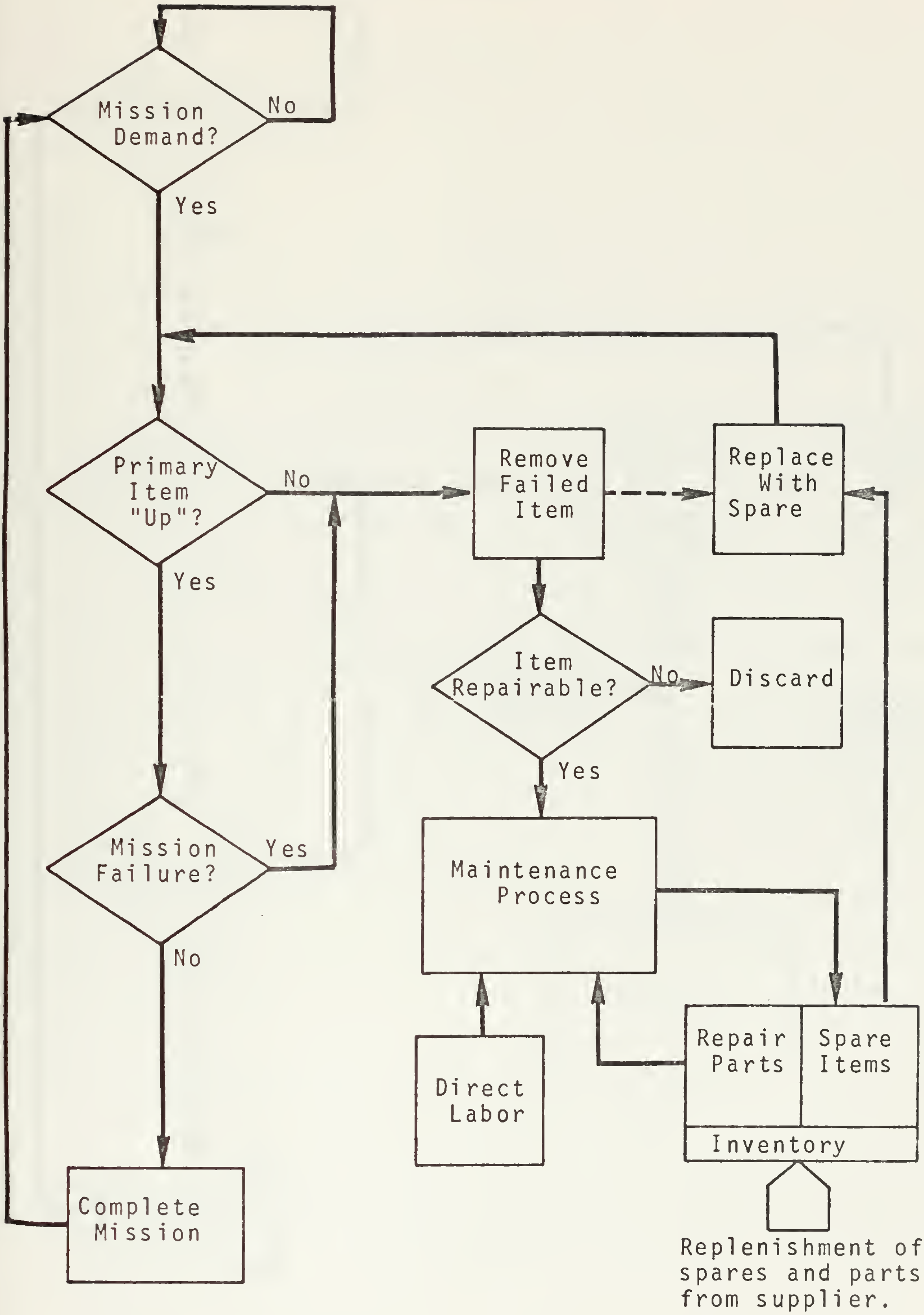

Figure (6)

LOGISTIC STRATEGY II

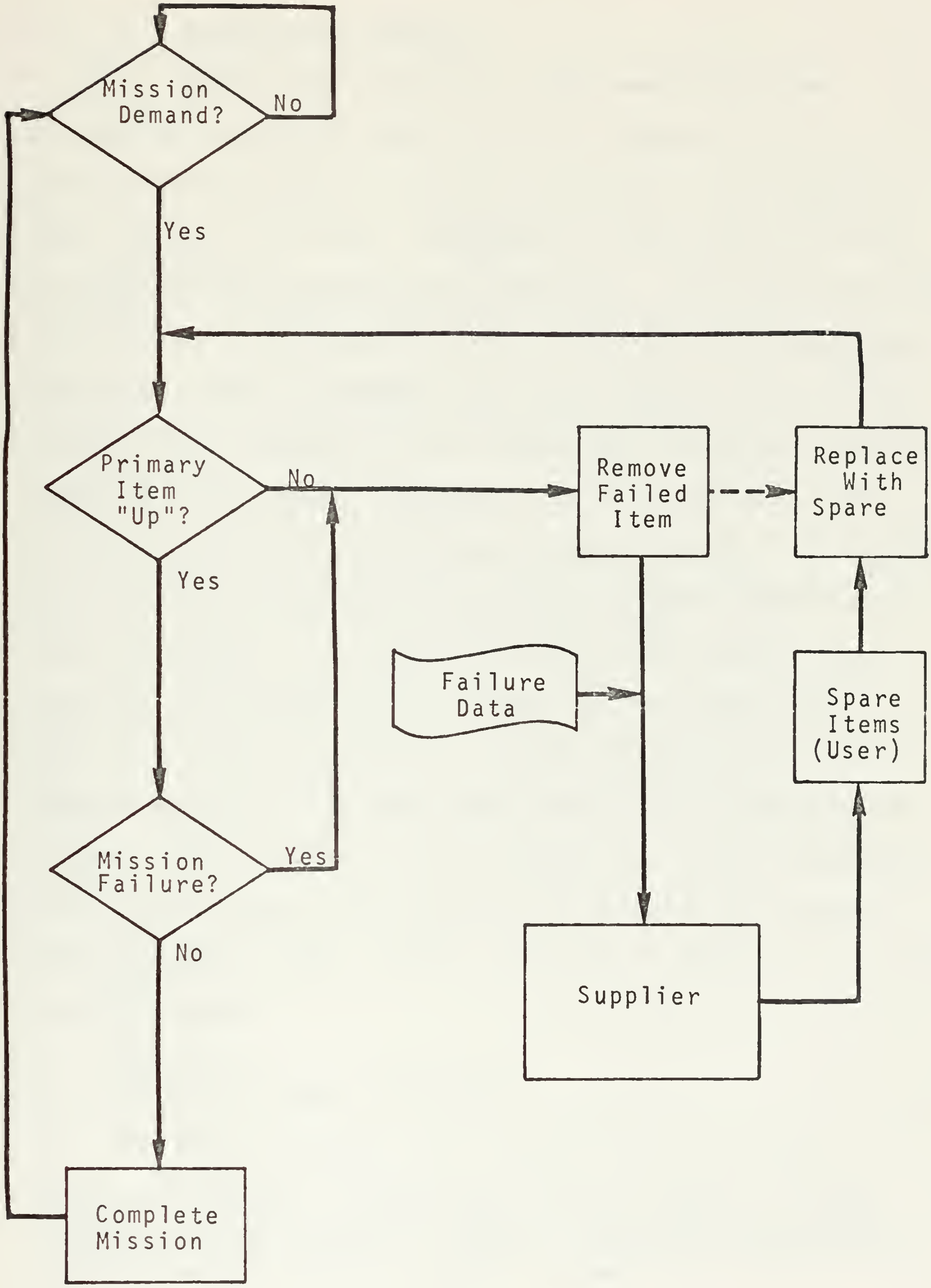

Figure (7)

3. Amplifying Comments

Under both strategies, the number of items on-hand at the user's facility at any given time is determined by a desired level of system E. The specific level of E is, in turn, influenced by the item R, M, and S specifications noted in the contract. It is expected that the Project Manager would initially procure this required number of items. Although the total would be essentially stable under Strategy I (all catastrophic failures would be replaced by new items purchased from the supplier), the warranty provisions of Strategy II would permit fluctuations as the supplier (acting as the design control agent) modified the design. Such modifications could result in an increase in item mean-time-between-failure (MTBF) not otherwise available under the limitations posed by user support except at the additional cost of retrofitting the system. The increase in item reliability (i.e., increased MTBF) could enable the supplier to increase his response time for failed units without violating a fixed E constraint for the system.

C. THE OPERATIONAL ENVIRONMENT

For these purposes, it is convenient to define:

Mission Demand: a requirement for an item (or items) to be in an operable and committable state (i.e., item availability) to begin a mission. Mission Demands are identified by discrete points in time.

Item Demand: the number of primary items required to satisfy a given Mission Demand.

Mission Duration: the length of time an item is required to be in an operating mode to fulfill a given Mission Demand. Mission Duration terminates with Mission Completion.

Defining an <u>event</u> as either a Mission Demand, Item Demand, or Mission Completion, the following assumptions are made:

- the probability that an event occurs during any very small interval of time Δt is equal to $\psi \Delta t$, where ψ is the mean number of occurrences of the event per unit time,

- the probability of the event occurring more than once during the interval Δt is zero, and

- the occurrence or nonoccurrence of the event during the interval $(t, t + \Delta t)$ does not depend on what happened prior to time t.

As such, the three events are independent random variables which reflect Poisson processes [Ref. 12].

To determine the particular points in time at which Mission Demands occur, one needs only to add in an aggregative manner the amount of elapsed time between successive Demands beginning with the point of system introduction, $t = 0$. It can be shown that the elapsed time is distributed exponentially:

$$f(t) = \alpha \cdot e^{-\alpha \cdot t} \quad , t \geq 0$$

$$= 0 \quad , \text{elsewhere}$$

where α = mean number of Mission Demands per unit time, and

t = number of units of elapsed time since the last Mission Demand.

Integrating f(t) over all values of t yields the cumulative distribution function:

$$F(t) = 1 - e^{-\alpha \cdot t} \quad , t \geq 0.$$

The probability that a Mission Demand does not occur before time t is given by $\bar{F}(t) = 1 - F(t)$:

$$\bar{F}(t) = e^{-\alpha \cdot t} \quad , t \geq 0.$$

The expected time between successive Mission Demands (MTBMD) is equal to $1/\alpha$.

The number of primary items required to satisfy a given Mission Demand at time t is found by applying the Poisson distribution:

$$f(n) = \frac{e^{-\alpha t} \cdot (\alpha \cdot t)^n}{n!}, \ n = 0, 1, 2, 3, \ldots$$

where α = mean number of Item Demands per unit time,

t = number of units of time, and

n = number of Item Demands.

To maintain independence between Mission Demand and Item Demand, a new value of t must be determined from the exponential distribution with parameter α. Utilizing this value $t = t^*$, the expected number of Item Demands given that a Mission Demand has occurred is equal to $\alpha \cdot t^*$.

In similar fashion, the Mission Duration can be established from:

$$\bar{F}(t) = e^{-\phi \cdot t} \quad , t \geq 0$$

where ϕ = mean number of missions (Item Demands) per unit <u>operating</u> time, and

t = number of units of <u>operating</u> time.

The expected Mission Duration is $1/\phi$.

D. SELECTING MEASURES OF E, R, M, AND S

In any analysis the selection of the appropriate measure of E (MOE) is of extreme importance. For it is this value which quantitatively expresses the amount of benefits to be realized from a particular course of action. To be useful, it should be easily determined in quantitative terms, be sensitive to changes in the important variable inputs, and exhibit a commonality among the differing system proposals. That is, one should avoid having to compare apples with oranges. Some candidates for a system MOE include:

- -operational ready rate: the percentage of assigned items capable of performing the mission or function for which they were designed when Mission Demand is a random point in time,
- -availability: the probability that an item is in an operable and committable state at the beginning of a mission when Mission Demand is a random point in time,
- -mean-time-between-failures (MTBF): the average time between item failures (operating hours),
- -mean-time-to-repair (MTTR): the average time to repair each failed item (maintenance manhours), and
- -probability of survival: the probability that a system will not reach a completely failed state during a given time interval.

It should be apparent that a departure from the definition of E proposed in Section V is being pursued. This is felt to be consistent with the level of analytical sophistication noted in previous paragraphs. To be sure, the proper level should be a function of the types of decisions under consideration.

In view of the maintenance processes and the operational environment, one may now investigate in additional detail the characteristics of the items within the system. If an item is either available (up) or unavailable (down) (i.e., a Bernoulli trail), item availability is constant and does not vary among items, and each item's operation and failure is independent of the remainder of the population, then the system is an ordinary renewal process [Ref. 13] which neatly fulfills the assumptions underlying the binomial distribution [Ref. 14]. It is now possible to select an MOE with the preferred attributes noted in the beginning of this discussion:

> System Availability ($\underline{A}$): the probability that at least P items out of the combined total of primary and spare items will be in an operable and committable state given a Mission Demand at a random point in time.

Mathematically, one may define this measure as:

$$\underline{A} = \sum_{j=P}^{j=N} \frac{N!}{j! \cdot (N - j)!} \cdot \underline{a}^{j} \cdot (1 - \underline{a})^{N-j}$$

where $\underline{A}$ = System Availability,

P = number of primary items,

N = total number of primary and spare items in the user's system, and

$\underline{a}$ = item availability.

Item availability may be defined as:

$$\underline{a} = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR} + \text{MRT}}$$

where MTBF and MTTR are the $\underline{R}$ and $\underline{M}$ specifications noted in the prospective contract under Strategy I (user support),

and MTBF and MRT are those included in Strategy II (MRT is defined as mean replacement time, the average elapsed time from item failure to receipt of the replacement). It is assumed that MRT will have a positive value under Strategy I equal to the average time required to obtain a repair part not in the active inventory, given that the part is needed to correct a failed item. Within the provisions of Strategy II, MTTR is equal to zero (it is implicit in MRT).

System Availability (A) is easily determined by substituting selected values of N and a into the expression. Additionally, it is both sensitive to the important variable inputs in the system (i.e., number of primary and spare items, R, M, and S specifications), and is applicable to both alternatives under consideration.

E. LIFE CYCLE PRIME COSTS OF SYSTEM OWNERSHIP

In the same manner as the E model just described, one should employ a life cycle cost estimating model which is sensitive to the important variable inputs. Such a model gives visibility to the effects input changes have on the total cost streams of the competitive alternatives.

1. Logistic Strategy I

User support requires that primary and spare items, and repair parts be procured at the time of system introduction, t = 0. The recurring dollar expenditures of direct labor, repair parts inventory replenishment, and the replacement of catastrophic failures is assumed to occur at a constant rate throughout the year. The cost of capital

invested in inventory, an opportunity cost not appearing on the user's "income" statement, is similarly treated. Salvage (terminal) values of items and repair parts is set equal to zero. The resultant cost profile is:

$$LCC_1 = IPC_1 + TSC_1$$

where LCC_1 = life cycle prime costs of system ownership ($)

IPC_1 = initial procurement cost ($)

TSC_1 = total support cost ($)

y = number of years of system operation

a. Initial Procurement Cost (IPC_1)

Initial Procurement Cost is equal to the sum of primary and spare items procurement cost and repair parts procurement costs:

$$IPC_1 = C_u \cdot N + \sum_{i=1}^{i=k} C_{ri} \cdot R_i$$

where C_u = unit procurement cost of items ($ per item)

N = total number of primary and spare items

C_{ri} = unit procurement cost of the ith repair part ($ per part)

R_i = total number of the ith repair part

k = number of different repair parts.

b. Total Support Cost (TSC_1)

Total Support Cost is equal to the sum of labor costs, item and repair part replenishment costs, and inventory investment costs:

$$TSC_1 = pvf \left[\left(C_\ell \cdot MTTR + C_u \cdot f + \sum_{i=1}^{i=k} C_{ri} \cdot r_i \right) \cdot \frac{OT}{MTBF} + \right.$$

$$\left. \left(C_u \cdot S + \sum_{i=1}^{i=k} C_{ri} \cdot R_i \right) \cdot d \right]$$

where pvf = present value of \$1 paid in a steady stream throughout y years in the future [Ref. 15]

C_ℓ = direct labor rate (\$ per maintenance manhour)

f = catastrophic failure rate (catastrophic failures per item failure)

r_i = replenishment rate of the ith repair part (ith parts per failure)

OT = system operating time (hours per year)

S = number of spare items

d = discount rate, the user's cost of capital (expressed as a percentage).

c. Amplifying Comments

Although most of the elements in the aggregate cost expression are intuitive, several do require further explanation. In the first place, repair parts procurement and replenishment costs are not developed in a more explicit manner because they are peculiar to the specific item in the system. The quantities of the particular parts to be maintained in the active inventory are a function of replacement time (supply response time), the number of parts per item subject to failure, failure rate per part, and unit procurement cost (C_{ri}). By simultaneously considering the

marginal product of each additional part, its marginal cost, and the MRT, the proper inventory mix can be developed to satisfy life cycle cost and <u>E</u> constraints. Karr and Geisler [Ref. 16] demonstrate the usefulness of such an application of marginal analysis to the selection of parts for an aircraft mobility package.

Secondly, system operating time (OT) may be determined from the operational parameters noted previously as follows:

$$OT = \frac{\alpha \cdot \partial}{\phi}$$

where α = average number of Mission Demands per year,

∂ = average number of Item Demands per Mission Demand, and

ϕ = average number of missions (Item Demands) per operating hour.

Thirdly, the term

$$\left(C_u \cdot S + \sum_{i=1}^{i=k} C_{ri} \cdot R_i \right) \cdot d$$

represents the annualized opportunity costs of maintaining the active inventory. It quantifies the alternate uses of capital forgone by implementing Strategy I. As such, it forces the Project Manager to recognize the limited amount of available capital and to use it efficiently.

Finally, the present value factor (pvf) reflects the time value of money. Costs occuring in out-years must be discounted to permit valid comparisons. While the actual

discount rate to be employed is subject to conflicting opinions, it should adequately weigh the Project Manager's preferences (utility) of near-term costs and future costs.

2. Logistic Strategy II

Supplier support requires that primary and spare items be procured at the time of system introduction as in Strategy I. For each item procured, the supplier shall charge the user an annual warranty fee. This obligates the former to meet a MRT specification for repaired items. Additionally, it demands that the supplier finance the requisite investment in spare items and repair parts to comply with this specification under the sanction of penalty fees. As failures occur, items are shipped with the relevant data to the supplier at the user's expense. Replacement item transportation expenses are borne by the supplier. The cost profile to the user under this Strategy is:

$$LCC_2 = IPC_2 + TSC_2$$

a. Initial Procurement Cost (IPC_2)

Initial Procurement Cost is equal to primary and spare items procurement costs:

$$IPC_2 = C_u \cdot N.$$

b. Total Support Cost (TSC_2)

Total Support Cost is equal to the sum of warranty costs, transportation costs, item replenishment costs, and inventory investment costs:

$$TSC_2 = pvf \cdot \left[C_w \cdot N + \left(C_t + C_u \cdot f \right) \cdot \frac{OT}{MTBF} + C_u \cdot S \cdot d \right]$$

where C_w = unit warranty cost ($ per item per year) and

C_t = unit transportation cost ($ per item).

To amplifying comments of Strategy I costs are valid under supplier support (except for repair parts procurement and replenishment considerations, which do not enter into the LCC_2 cost profile.

F. SOURCES OF DATA

The Government-Industry Data Exchange Program (GIDEP) and the Failure Rate Data Program (FARADA) are two ongoing efforts concerned with the interchange of technical data related to parts, components, materials, failure rate, failure mode, and testing. Reference 17 identifies 23 Government R and M data sources and 95 sources of technical and scientific information for related engineering data. It also lists the R and M data collection activities of 94 contractors. These sources should enable the Project Manager to establish a state-of-the-art threshold for items he will be procuring.

G. CRITERIA

The defined cost and E structure permits the use of either of the two optimization methodologies described earlier.

H. USE OF THE MODEL

The system model establishes relationships among R, M, and S, permits tradeoffs among their particular parameters, and makes the effects of these tradeoffs visible in terms of life cycle prime costs and system E.

Given values of A and P, the Project Manager can determine the attainable combinations of N, MTBF, MTTR, and MRT consistent with the E criterion. This procedure can be facilitated by plotting isoavailability curves for the system as a function of N and a. All points on such a line would satisfy the system constraint. The next step involves computing the least cost combinations of item quantity and logistics specifications under both strategies, and comparing the results. The explicit use of the defined variables in both the cost and E expressions permits an analysis of their relative impacts as each is varied throughout a relevant range of values while the others remain constant.

To determine the unit warranty cost indifference point (i.e., the point at which one would be indifferent to either strategy), one need only to equate the alternative cost profiles:

$$C_w = \frac{\sum_{i=1}^{i=k} C_{ri} \cdot R_i}{pvf \cdot N} + \frac{\left(C_\ell \cdot MTTR + \sum_{i=1}^{i=k} C_{ri} \cdot r_i - C_t\right) \cdot OT}{N \cdot MTBF} + \frac{d \cdot \sum_{i=1}^{i=k} C_{ri} \cdot R_i}{N}.$$

That is, if the supplier offered a unit warranty price which was less than the value of the expression on the right, it would be less costly in life cycle terms to attain the prescribed level of $\underline{A}$ by selecting Logistic Strategy II.

The operation of the system throughout its lifetime may be simulated by utilizing Monte Carlo techniques and supplementing the probability distributions describing the operational environment with appropriate functions of time to failure, repair, and replace. If items will eventually consist of repair parts of varying ages, the exponential distribution with parameter λ is a useful description of the time to failure ($\lambda = 1/MTBF$, failures per unit time) [Ref. 18]. Maintainability literature holds that either the exponential or lognormal distributions may be used to define time to repair. Goldman and Slattery [Ref. 19] note:

> The exponential tends to fit the type of equipment that requires relatively frequent adjustments of very short durations or which may be put back into service via a quick remove and replace operation...The lognormal distribution describes the downtime for a wide variety of reasonably complex equipments. This distribution is useful in describing the situation where there are few downtimes of short duration, a large number of observations closely grouped about some modal value, and a not insignificant number of long downtimes.

The obvious analogy of repair time and replacement time may guide the selection of an appropriate function for the latter.

Although the specifics of the simulation process have been sacrificed somewhat by utilizing expected values, it is felt that the selected approach is more consonant with the kind of information found during the conceptual and validation phases [Ref. 20].

VII. CONCLUSIONS

The focus of this report was to present a general methodology for evaluating the costs and effectiveness of two logistics strategies which included significant life cycle concepts. As an analytical technique it can only aid in decision-making and cannot overcome the deleterious effects of premature decisions. As such, the system model should be considered as a supplement to judgement and experience. Undoubtedly the real-world procurement problem is dynamic and difficult to assess in the deterministic manner suggested herein. However, even though the defined system was a first approximation of reality, it did permit an insightful examination of some of the more important aspects of R, M, and S specifications without the need for mathematical complexity. In particular, the cost profiles include the elements found to be significant in commercial airline operations [Ref. 21]. Notwithstanding, one would be remiss not to indicate "soft" areas where further research is required.

In this regard, the wisdom of specifying item MTBF, MTTR, and MRT goals in a contract is not apparent. To do so suggests that the Project Manager knows the optimal tradeoff point among R, M, and S for the items to be procured. Intuitively, it appears that a more prudent course of action would be to specify an item availability goal, and permit the supplier to make logistics allocation decisions within

prescribed limits. A second topic is the explicit impact of logistics specifications on item unit procurement cost (C_u). Although an exponential functional form has been suggested [Refs. 22 and 23], the apparent importance of these factors on the costs of ownership demands that the relationships be more firmly established.

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